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Carbon footprint of the hot-dip galvanisation process using a life cycle assessment approach

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ABSTRACT

This work presents the carbon footprint (CF) of two hot-dip galvanisation (HDG) installations located in Spain with differences in the galvanising capacity and in the manufacturing process. The study determines the influence of the direct emissions (scope 1), emissions from electricity production (scope 2), and indirect emissions from upstream and downstream processes (scope 3). The results showed that steel and primary zinc production were the principal contributors to the CF. So, efforts should be focused on reducing the impact of the raw material production included in scope 3. Furthermore, two sensitivity analyses are presented: i) the production of one kg of two types of zinc products, special high-grade and redistilled zinc; ii) the use of two coatings: zinc for galvanisation and paint for pre-printed steel. The environmental impacts in SHG zinc were higher than in redistilled zinc, for all the impact categories due to the great influence of heavy metals emission. The results for zinc and paint protections showed that under the same level of corrosion, a greater thickness of paint is needed to protect steel pieces, compared to zinc coating. This sustainability assessment of the HDG industry recommends the sought of technology alternatives aimed at resource efficiency, such as zinc recovery from spent pickling baths, that could provide the desirable reduction of the environmental impacts associated to primary resource usage and waste treatment.

1. Introduction

1.1. The hot-dip galvanising process

World crude steel production reached 1868.8 Mt in 2019 (Fig. 1), showing an increasing trend since the 90s that was only interrupted by the economic crisis of 2009. China was the main producer in 2019 with 996.3 Mt of steel, more than half of the worldwide production (51.3%), while Europe accounted for 8.5% in the same period, Spain representing the 17th global position and the 4th position at the European scope with 13.6 Mt of crude steel produced in 2019 (World Steel Association, 2019). Steel production requires a great amount of energy and extraction of non-renewable resources, mainly iron. Specifically, the steelmaking industry is the largest energy consumer in the world, and almost 27% of the global CO_2 emissions are derived from this sector (Jaimes and Maroufi, 2020). Some measures to reduce greenhouse gases (GHG) emissions from the steel industry are scrap recycling, the use of carbon free-energy, and the production of high-performance steel to extend its lifespan and to reduce steel corrosion that generates relevant monetary losses (Fresner et al., 2007). Scrap recycling reduces GHG emissions since the impacts of using one kg of scrap to produce steel are much lower than those of one kg of pig iron, as scrap does not go through the stages of mining, refining, and melting (Tongpool et al., 2010).

Regarding steel protection, zinc coating protects steel from corrosion by the formation of a passive layer that simultaneously provides a sacrificial anode (Nakhaie et al., 2020). The durability of protection depends on the zinc layer thickness and the environmental exposure conditions (Kovalev et al., 2019). The hot-dip galvanising (HDG) method is one common and effective solution to protect steel structures from corrosion. The negative aspects of the galvanising industry include the intensive use of energy and primary zinc (Urtiaga et al., 2010). Fig. 1 shows that crude steel production is clearly linked to zinc production, the latter accounting for one-hundredth of steel production. Although zinc represents a low percentage by weight of galvanised steel components, the environmental burdens of zinc are distinctively high. Tongpool et al. (2010) evaluated the production of both steel and primary zinc, using some impact categories such as Abiotic Depletion of fossil fuels (ADP--fossil), Abiotic Depletion of elements (ADP-elements) and Global Warming Potential (GWP). The impacts of zinc production were always higher than the impacts of steel production, e.g.: almost three times higher for ADP-fossil, more than one hundred times greater in

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Abbreviations

ADP-elements	Depletion of Abiotic Resources-Elements
ADP-fossil	Depletion of Abiotic Resources-Fossil
AP	Acidification Potential
BSI	British Standards Institution
CF	Carbon Footprint
C2	Corrosivity category of low level
C3	Corrosivity category of medium level
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
FU	Functional unit
GDP	Gross Domestic Product
GHG	Greenhouse gas
GWP	Global Warming Potential
HDG	Hot-dip galvanising
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
MAETP	Marine Aquatic Ecotoxicity Potential
ODP	Ozone Layer Depletion Potential
POCP	Photochemical Ozone Creation Potential
SHG zinc	Special high-grade zinc
SPA	Spent Pickling Acid
TETP	Terrestrial Ecotoxicity Potential
ULCOS	Ultra Low CO_2 Steelmaking
WRI	World Resources Institute
WBC SD	World Business Council for Sustainable Development

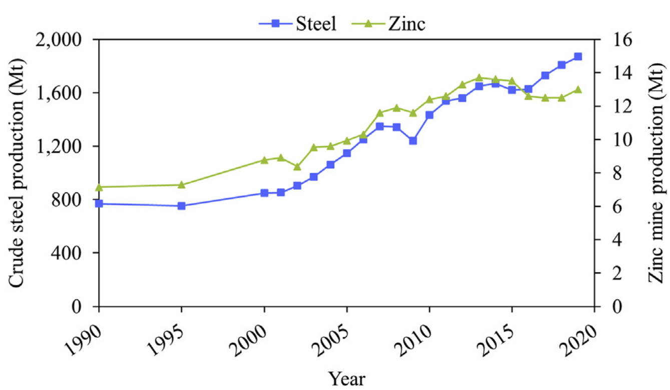

Fig. 1. Crude steel and primary zinc productions. Data taken from (United States Geological Survey (USGS), 2019; World Steel Association, 2019).

ADP-elements, and three times higher in the case of GWP. Thus, one important challenge of the galvanisation sector, is to reduce its environmental impacts linked to the intensive use of energy and resources.

1.2. The hot-dip galvanising process and life cycle assessment

In the literature, the environmental assessment of steel production has been studied using tools such as life cycle assessment (LCA). Liu et al. (2020) used LCA methods to assess the impacts of five iron top-mining countries and ten steel top-producing countries. Results concluded that toxicity impacts were the most crucial consequences of this sector, even higher than the impacts of CO_2 emissions. The European initiative "Ultra Low CO_2 Steelmaking (ULCOS)" to reduce CO_2 emissions by 50% by 2050, enables the use of LCA to compare alternative metallurgical technologies (Burchart-Korol, 2011). Previous works have evaluated the environmental impacts of different products that employ a zinc coating for corrosion protection. Bolin and Smith (2011) performed the environmental comparison between borate-treated lumber used as structural framing with galvanised steel framing members. Cambria and Pierangeli (2012) identified the hot spots of high-quality timber production from a dedicated walnut tree plantation that includes galvanised steel components for plants protection. Ansah et al. (2020) compared the environmental and economic burdens of different facade systems in low-cost residential buildings in Ghana, one of them being the galvanised steel insulated facade. However, few studies have investigated the environmental performance of HDG processes. This factor indicates the need to evaluate the galvanisation process by means of environmental tools to provide insights into the environmental sustainability of HDG. Spain is the fourth country in installed capacity and production in the Eurozone, and galvanised steel production was 15% higher in 2019 than in the previous year, reaching $650 \cdot 10^3$ t/y (Spanish Technical Association of Galvanisation, 2020). This sector also takes economic importance since corrosion costs represent 4% of the national Gross Domestic Product (GDP), which implies more than $40 \cdot 10^3$ MEUR/y. In Spain, the HDG sector consists of 43 small and medium-size facilities with profits higher than 200 MEUR/y and with more than 3000 direct jobs (Spanish Technical Association of Galvanisation, 2020). Galvanised steel is mostly consumed by the energy generation and distribution sector (40%), followed by building and construction, which uses 25% of the total production. Other common applications are road elements, industrial equipment, and transport.

There is a higher worldwide trend of simplification focusing on a single indicator, carbon footprint (CF) that is relevant to global warming (Kosai and Yamasue, 2019). CF can be assessed at product or corporate level. Product CF follows LCA methodology, but analyses only the impact in terms of kg CO_2 eq., and it is based on standards such as ISO 14067 (2013), PAS 2050 (BSI, 2011) or GHG Protocol for products (WRI and WBC SD, 2011a). CF at corporate level is carried out following the standards ISO 14064 (2006) or GHG protocol (WRI and WBC SD, 2004). In the same vein as the LCA and the HDG process, there is a gap in the literature on adopting a carbon footprint approach for the galvanising sector.

1.3. Aim of the study

This study aimed to evaluate the environmental performance of the HDG sector in Spain, based on data from two HDG plants, which are very representative of the galvanising sector of the country in order to identify the contribution of each scope to the total carbon footprint in both facilities. Through the total CF is possible to place these plants within the Spanish galvanising sector and reach conclusions about the consequences of the differences between both facilities. CF was calculated at three scopes: 1) direct emissions, 2) emissions from electricity production and 3) indirect emissions from upstream or downstream processes. Considering the influence of resource use, two sensitivity analyses were conducted. In the first analysis, the production of two types of primary zinc was assessed. Secondly, primary zinc production was compared with the production of paint used as corrosion protective coating of steel structures. The analysis of zinc production included other impact categories in addition to the CF to consider the toxicity of zinc mining and refining, as the impact categories related to toxicity should be considered (Liu et al., 2020).

This paper constitutes the first Corporate Carbon Footprint of the HDG process based on two Spanish HDG plants. The analysis including the three CF scopes allows to identify the hot spots of the HDG process focusing on a single indicator relevant to global warming, which adds a simplification to the analysis and interpretation of the results. In addition, the sensitivity analysis of zinc production, and the comparison between zinc and paint production could provide significant improvements to the HDG sector.

2. Methodology

Carbon footprint based on ISO 14064 (2006) and GHG corporate protocols (WRI and WBC SD, 2011b) was used to determine the GHG emissions of two HDG plants located in Spain. CF measures the total GHG emissions that are directly and indirectly caused by a human activity, including those accumulated over the life stages of a product (Clabeaux et al., 2020). World Resources Institute (WRI) and World Business Council for Sustainable Development (WBC SD) define three scopes. Scope 1 includes direct GHG emissions from sources that are owned or controlled by the company. Scope 2 refers to the upstream emissions from the generation of purchased electricity, and scope 3 comprises indirect GHG emissions that are a consequence of the company's activities. Scope 3 can be divided in upstream (raw materials extraction and its transportation), and downstream processes (waste management). Scope 3 can be excluded in the corporate CF produced by companies, albeit, the present work includes those indirect emissions. Life cycle methodology following ISO 14044 (2006) is used to quantify indirect emissions included in the scopes 2 and 3 (Navarro et al., 2017). In this work, indirect emissions were calculated by questionnaires completed by the companies for 2016 and 2017. The HDG plants under study, HDG plants #1 and #2, are referred as scenarios 1 and 2 throughout this study. The data inventory for both scenarios is shown in Table S1.1 as Supplementary Material. Secondary data come from Sphera (professional database 2020) and Ecoinvent (version 3.6) databases (Ecoinvent, 2020; Sphera, 2020). The reference unit used has been defined as the production of one tonne of galvanised steel. This can be considered as the functional unit (FU) although in Corporate Carbon Footprint studies there is no functional unit (Navarro et al., 2017). Carbon footprint is focused on a single indicator relevant to global warming, which is measured in kg of CO_2 equivalent emissions. CML 2001 updated in 2016 has been selected to include other impact categories for the sensitivity analysis of primary zinc production. These impact categories are: abiotic depletion of elements (ADP-elements) [kg Sb eq.], abiotic depletion of fossil fuels (ADP-fossil) [MJ], acidification potential (AP) [kg SO_2 eq.], eutrophication potential (EP) [kg PO_4^{3-} eq.], freshwater aquatic ecotoxicity potential (FAETP) [kg DCB eq.], human toxicity potential (HTP) [kg DCB eq.], marine aquatic ecotoxicity potential (MAETP) [kg DCB eq.], photochemical ozone creation potential (POCP) [kg ethene eq.], and terrestrial ecotoxicity potential (TETP) [kg DCB eq.].

2.1. System boundaries

Fig. 2 describes the flow diagram and system boundaries of the industrial installations that have been named as scenario 1 and scenario 2. The differences between the two HDG facilities (scenarios 1 and 2) are explained in section 2.2. The scope of the study included the extraction of resources, the production of raw materials including steel, their transport to the galvanising plants, the galvanisation process itself, waste treatment and transport to waste management facilities, and its final disposal. The usage and end-of-life phases of the galvanised steel were not included. Buildings and machinery were excluded from this analysis since their environmental impacts were very small compared with the impacts of steel production and the HDG process (Heinonen et al., 2016).

Within the HDG process the main stages were degreasing, pickling, fluxing, drying, immersion in the molten zinc bath and centrifugation (Ortiz et al., 2004). The main raw materials inputs are primary zinc and hydrochloric acid. Primary zinc is used in the molten zinc bath where steel pieces are immersed to acquire the zinc coating. Hydrochloric acid is employed in the pickling stage to remove impurities and oxides from the surface of steel pieces. Natural gas is the main energy vector in both scenarios, although electricity is also consumed. Natural gas is employed to produce thermal energy that is used to dry the steel pieces before their immersion into the molten zinc bath. The degreasing and pickling baths also require heating, but to a much lesser extent (European Commission, 2001). Spent pickling acids (SPAs) are one of the most relevant wastes that are generated in the HDG process. SPAs are usually handled in external waste management facilities by a physicochemical treatment whose outputs are treated water and hazardous sludge, the latter once stabilised in sent to a non-hazardous waste landfill (Devi et al., 2014). Both scenarios also generate other important residues, identified as ashes and dross, both with high content of metallic zinc (Rudnik, 2019). Ashes and dross are valorised to produce secondary zinc and/or zinc oxide, following processes that are not included in this study (Negrea et al., 2017). Direct emissions from natural gas extraction and its combustion to produce thermal energy are included in the scope 1. The indirect emissions from purchased electricity is covered by the scope 2. The production of raw materials and their transport to the HDG plants are upstream

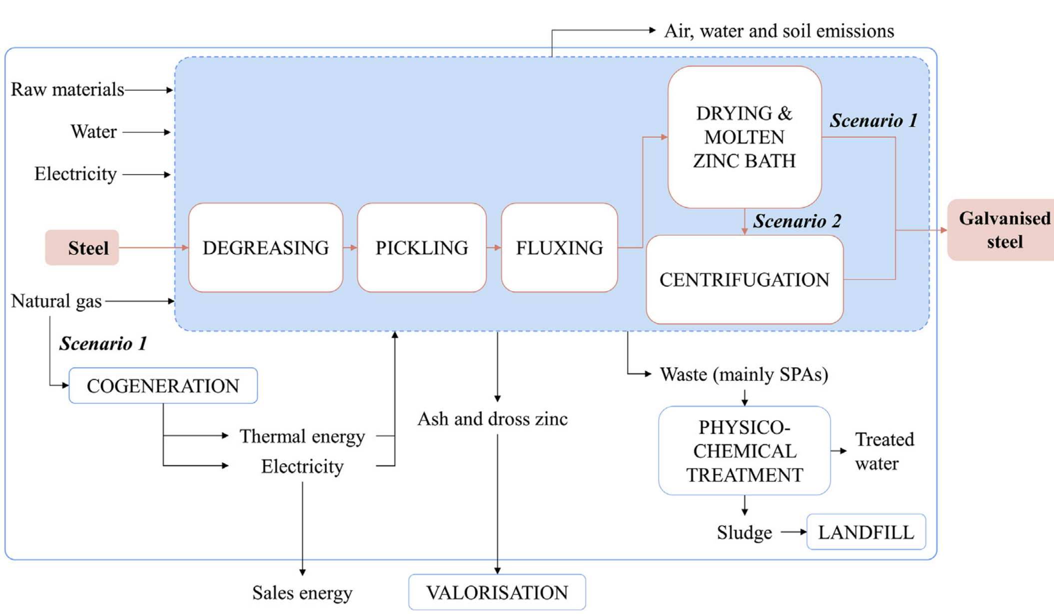

Fig. 2. System description of the hot-dip galvanisation process in scenarios 1 and 2.

processes that belong to scope 3. Finally, waste management and disposal on landfill and their transport are downstream processes of scope 3. The production of $ZnCl_2$ and NH_4Cl salts used in the fluxing stage and zinc alloys added in the molten zinc bath have been excluded from the study. This exclusion is based on the cut-off criteria, which established that the material flows that are excluded must not exceed 1% of the mass of each unit process and the sum of all excluded material flows in the system must not exceed 5.0% of the total mass flux.

2.2. Description of scenarios

Both scenarios have the same purpose, that is to galvanise steel pieces by the HDG process in a discontinuous way. Next, we explain the differences between the two scenarios.

Scenario 1. The galvanising capacity of scenario 1 was $51.4{\cdot}10^3$ and $78.7{\cdot}10^3$ t galvanised steel/y in 2016 and 2017. Steel pieces are mostly employed for building and civil infrastructure. Scenario 1 presents a cogeneration unit to produce thermal energy and electricity to supply the energy of drying and baths heating. All the thermal energy and one part of the electricity is employed in the galvanisation process, but a relevant portion of the electricity is sold to the grid mix obtaining potential benefits.

Scenario 2. Scenario 2 has a galvanisation capacity of $3.5{\cdot}10^3$ and $4.85{\cdot}10^3$ t galvanised steel/y in 2016 and 2017. Steel pieces are smaller in size, and are employed in the manufacturing of machinery, e.g.: in the assembly of wind turbine structures. This causes the incorporation to the HDG process of an additional centrifugation stage in order to remove excess of liquid zinc from galvanised pieces. One of the main differences between both scenarios is that scenario 2 does not incorporate cogeneration.

3. Results and discussion

The results obtained in the present study represent the environmental impacts of both scenarios for 2016. Table 1 summarises results from 2016 to 2017, where it can be observed that the outcomes were similar in the consecutive years, a consequence of the inventory being practically stable.

3.1. Carbon footprint analysis

Fig. 3 shows the contribution in percentage and the total value of the CF (kg CO_2 eq./t steel) in scenarios 1 and 2 for 2016. These results include the valorisation of scrap and the energy credits obtained from cogeneration in the first scenario.

The total CF (as sum of scopes 1, 2 and 3) was 1796 and 1477 kg CO_2 eq./t galvanised steel in scenarios 1 and 2. The total CF is higher in scenario 1 due to the contribution of steel production that will be discussed in Fig. 4. Direct emissions included in the scope 1 are derived from the combustion of natural gas, with a very low contribution of propane in the first plant. The contribution of natural gas is higher in the second scenario (12.9% vs. 9.3%) since the cogeneration unit improves the overall environmental performance of scenario 1. In other words, scenario 1 is more efficient than scenario 2 regarding the obtention of

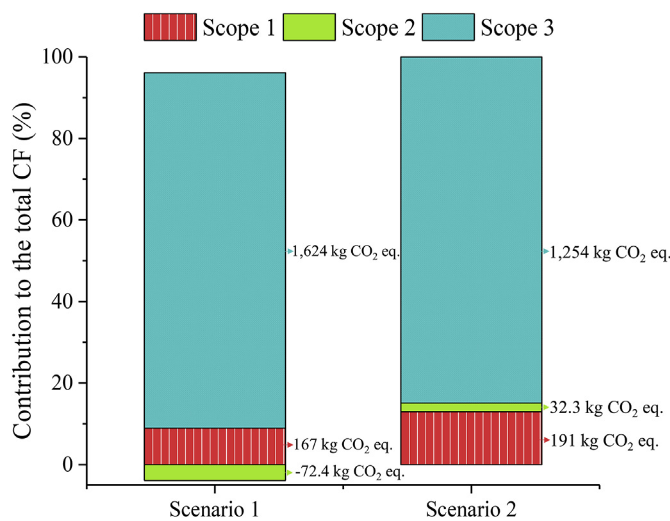

Fig. 3. CF (kg CO_2 eq./t galvanised steel) and contribution of each scope for scenarios 1 and 2 in 2016, including scrap valorisation (scope 3 downstream) and energy credits from cogeneration (scope 1).

Table 1
Carbon footprint (kg CO_2 eq./t galvanised steel) for scenarios 1 and 2.

	kg CO_2 eq./t galvanised steel				Contribution to the total CF (%)			
	Scenario 1		Scenario 2		Scenario 1		Scenario 2	
	kg CO_2 eq./FU				%			
	2016	2017	2016	2017	2016	2017	2016	2017
Natural gas	166.70	151.65	191.06	159.70	9.30	8.50	12.9	11.3
Propane	$9.33{\cdot}10^{-2}$	$7.73{\cdot}10^{-2}$	–	–	$5.20{\cdot}10^{-3}$	$4.35{\cdot}10^{-3}$	–	–
Electricity	$2.44{\cdot}10^{-1}$	$8.74{\cdot}10^{-2}$	32.30	23.30	$1.36{\cdot}10^{-2}$	$4.92{\cdot}10^{-3}$	2.2	1.6
Steel	1440	1440	1020	1022	80.2	81.1	69.0	72.2
Zinc	163.98	158.66	220.43	202.72	9.1	8.9	14.9	14.3
HCl	10.40	10.81	3.73	2.83	$5.79{\cdot}10^{-1}$	$6.09{\cdot}10^{-1}$	$2.52{\cdot}10^{-1}$	$2.00{\cdot}10^{-1}$
Wire	3.76	4.44	–	–	$2.09{\cdot}10^{-1}$	$2.50{\cdot}10^{-1}$	–	–
H_2O_2	3.31	2.15	0.34	0.18	$1.84{\cdot}10^{-1}$	$1.21{\cdot}10^{-1}$	$2.29{\cdot}10^{-2}$	$1.25{\cdot}10^{-2}$
NH_3	1.57	1.35	1.38	1.71	$8.75{\cdot}10^{-2}$	$7.63{\cdot}10^{-2}$	$9.31{\cdot}10^{-2}$	$1.21{\cdot}10^{-1}$
NaOH	$1.37{\cdot}10^{-1}$	$1.76{\cdot}10^{-1}$	–	–	$7.65{\cdot}10^{-3}$	$9.89{\cdot}10^{-3}$	–	–
KOH	$1.03{\cdot}10^{-1}$	$1.32{\cdot}10^{-1}$	–	–	$5.74{\cdot}10^{-3}$	$7.42{\cdot}10^{-3}$	–	–
Tap water	$8.93{\cdot}10^{-2}$	$6.81{\cdot}10^{-2}$	$9.52{\cdot}10^{-2}$	$8.97{\cdot}10^{-2}$	$4.97{\cdot}10^{-3}$	$3.84{\cdot}10^{-3}$	$6.44{\cdot}10^{-3}$	$6.33{\cdot}10^{-3}$
Pallets	−1.22	−0.99	–	–	$-6.78{\cdot}10^{-2}$	$-5.56{\cdot}10^{-2}$	–	–
Wood	−1.73	−2.86	–	–	$-9.65{\cdot}10^{-2}$	$-1.61{\cdot}10^{-1}$	–	–
HF	–	–	0.14	0.24	–	–	$9.54{\cdot}10^{-3}$	$1.71{\cdot}10^{-2}$
H_3PO_4	–	–	$3.50{\cdot}10^{-2}$	$3.73{\cdot}10^{-2}$	–	–	$2.37{\cdot}10^{-3}$	$2.64{\cdot}10^{-3}$
Transport of raw materials	6.94	6.76	1.94	2.91	$3.86{\cdot}10^{-1}$	$3.81{\cdot}10^{-1}$	$1.32{\cdot}10^{-1}$	$2.05{\cdot}10^{-1}$
Transport of waste	$9.31{\cdot}10^{-1}$	1.72	5.76	0.28	$5.18{\cdot}10^{-2}$	$9.68{\cdot}10^{-2}$	$3.90{\cdot}10^{-1}$	$1.97{\cdot}10^{-2}$
Waste management	0.57	0.41	0.28	0.17	$3.18{\cdot}10^{-2}$	$2.30{\cdot}10^{-2}$	$1.91{\cdot}10^{-2}$	$1.17{\cdot}10^{-2}$
TOTAL	1795.87	1774.65	1477.49	1416.60	–	–	–	–
Energy credits from cogeneration	−72.60	−57.56	–	–	–	–	–	–
Scrap valorisation	−4.94	−6.00	–	–	–	–	–	–
TOTAL	1718.33	1711.09	1477.49	1416.60	–	–	–	–

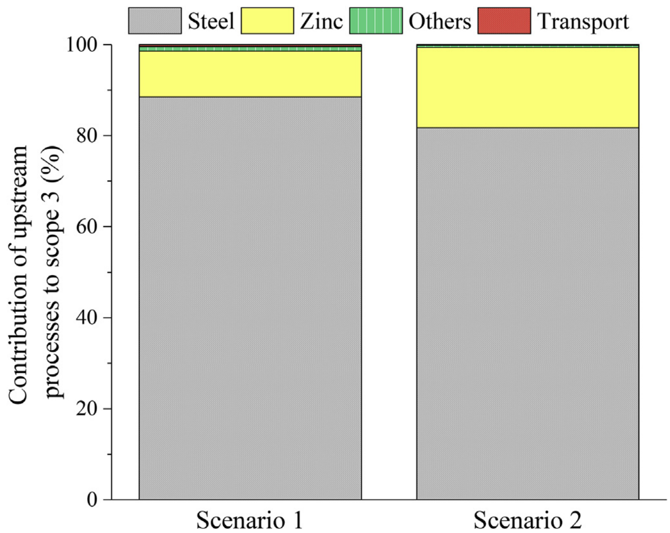

Fig. 4. Contribution of upstream processes for scenarios 1 and 2 in 2016, including scrap valorisation and energy credits from cogeneration.

thermal energy from natural gas. Indirect emissions due to the electricity consumption have a very low contribution to the total CF (0.0014 and 2.2% in scenarios 1 and 2). In both scenarios, the highest impact is attributed to indirect emissions included in the scope 3, with a contribution to the total CF of 91% and 85% in scenarios 1 and 2. The scope 3 is divided into upstream (raw materials) and downstream (waste) processes. The upstream processes represent in both plants more than 99% of the impact of scope 3. In this context, Fig. 4 shows the contribution of the upstream processes for both scenarios separated in steel, zinc, and other raw materials. Other raw materials in scenario 1 are NH_3, KOH, NaOH, wood, pallets and tap water. In scenario 2, other raw materials are HF, H_3PO_4, H_2O_2, NH_3 and tap water. Transport of raw materials to the HDG plants is included. Downstream processes represent a very low contribution to the total CF (0.08 and 0.41% in scenarios 1 and 2) as Table 1 shows. In addition, scrap valorisation provides material credits in scenario 1 (−4.94 kg CO_2 eq./t galvanised steel).

As Fig. 4 shows, the CF is linked to the raw materials extraction and manufacturing, with a low influence of the transportation on the overall results. Steel was the main contributor in both scenarios (more than 80% of upstream impact), although this percentage is higher in scenario 1. In the first scenario, the steel sections have a higher CF than the engineering steel applied in the second scenario. The selection of a representative steel has a great influence on the results since steel production is one of the main impacts of the HDG process. In fact, there is a huge variability of impact results for different types of steel. For instance, the CF of "engineering steel", "steel sections", "steel rebar" and "steel plate" is 1, 1.49, 2.29 and 2.52 kg CO_2 eq./kg steel.

Primary zinc is the other important material in scope 3, accounting for 10–20% of the CF of upstream processes. The contribution of zinc production to the scope 3 was greater in the scenario 2 since its consumption per tonne of galvanised steel is higher. Raw materials production provided in Table 1 denoted its low contribution in both scenarios.

As it was mentioned before, the electricity consumption has a very low contribution to the total CF although it is much higher in scenario 2 than in scenario 1. Concerning other raw materials, the consumption of HCl is much higher in the first scenario, albeit, the contribution to the total CF is only 0.6%. The rest of raw materials has a similar contribution. The CF contribution of the transport of raw materials to the HDG plants is much higher in the first scenario (6.96 vs 1.94 kg CO_2 eq./t galvanised steel in 2016). This tendency is the contrary for the transport of waste, which is higher in the second scenario in the same year. Besides, the CF caused by waste management is highly dependent by the amount of SPA generated. Wood and pallets had negative impacts since the CF includes biogenic carbon, meaning that these materials capture and fix carbon dioxide. In case of excluding biogenic carbon, the CF changes from −1.22 to 0.35 kg CO_2 eq./t galvanised steel for pallets, and from −1.73 to 1.16 kg of CO_2 eq./t galvanised steel in the case of wood.

3.2. Sensitivity analysis of zinc production

Considering the significant contribution of upstream processes to the CF of HDG industrial facilities, this section evaluates the environmental impacts of using two types of primary zinc. The sensitivity analysis presented in this section includes other impact categories based on the CML 2001 impact assessment method.

Fig. 5 shows the environmental impacts for producing 1 kg of special high-grade zinc (SHG) and redistilled zinc. Primary zinc is produced in two consecutive phases, the first one being the production of zinc concentrates that involves mining and beneficiation, followed by the metal zinc production (Van Genderen et al., 2016). Metal zinc production can be carried out by electrometallurgical or pyrometallurgical smelting. The main difference between them is that the electrometallurgical route uses zinc concentrate as input, and the pyrometallurgical route can also use secondary zinc. For this reason, the pyrometallurgical process produces zinc with lower purity than the electrometallurgical route. The electrometallurgical way comprises roasting, leaching, purification, electrolysis and melting. In pyrometallurgical smelting, the unit operations are sintering, smelting, and refining. The smelting furnace is an energy-intensive process that needs of high temperatures to reduce zinc oxide in the presence of coke, to zinc in vapor phase. After the stages of leaching and purification, some metals contained in the ore mines such as lead, copper and cadmium are separated to produce refined metals (Van Genderen et al., 2016). It is estimated that 90% and 92% of the SHG and "redistilled" zinc are obtained by the electrometallurgical route.

The environmental impacts are higher for SHG zinc, compared to the "redistilled" zinc, in all the impact categories except for ADP-elements and ADP-fossil, although the differences in this last category are minimal. GWP and ADP-elements are similar for the two types of zinc. ADP-elements is influenced by the impact of silver, which is a by-product of primary zinc production, but is not considered as such in the Sphera database. Nevertheless, the impact of lead explains the increase of the ADP-elements impact of "redistilled" zinc, which is eight times higher than in SHG production. This can be influenced by the quality of the ore mine, that in case of containing lead could enable the beneficiation of this metal after leaching in the electrometallurgical route (Van Genderen et al., 2016). ADP-fossil and GWP are similar between both types of zinc because the differences between natural gas and hard coal consumption and CO_2 emissions are minimal. The more relevant differences between both types of zinc are found in HTP and TETP. HTP is much higher for SHG zinc, due to the emission to air of arsenic (+V), cadmium and copper. Cadmium and copper can be obtained after the purification stage in the electrometallurgical route (Van Genderen et al., 2016), and arsenic is a by-product of the smelting of copper, lead and zinc concentrates (Nelson, 1977). The contribution of "redistilled" zinc to HTP is caused by arsine (AsH_3), with negative effects on health, such as cancer and cardiovascular disease that have been associated with long-term exposure to arsenic in humans (Wang et al., 2006). TETP is much higher for SHG zinc because of the mercury emissions to air. The reason is that zinc ore usually contains trace amounts of mercury, that make zinc smelting a relevant source of mercury emissions in the nonferrous metal industry (Takaoka et al., 2017).

EP and FAETP are more than four times higher in SHG zinc than in "redistilled" zinc. The differences in EP are attributed to the emission of nitrogen oxides to air. In both types of zinc, FAETP is motivated by the emission of heavy metals to freshwater, although the difference between both types is due to the copper emissions. AP, MAETP and POCP are almost two times higher for SHG zinc than for "redistilled" zinc. AP and POCP are caused by the emissions of sulphur dioxide and nitrogen oxides

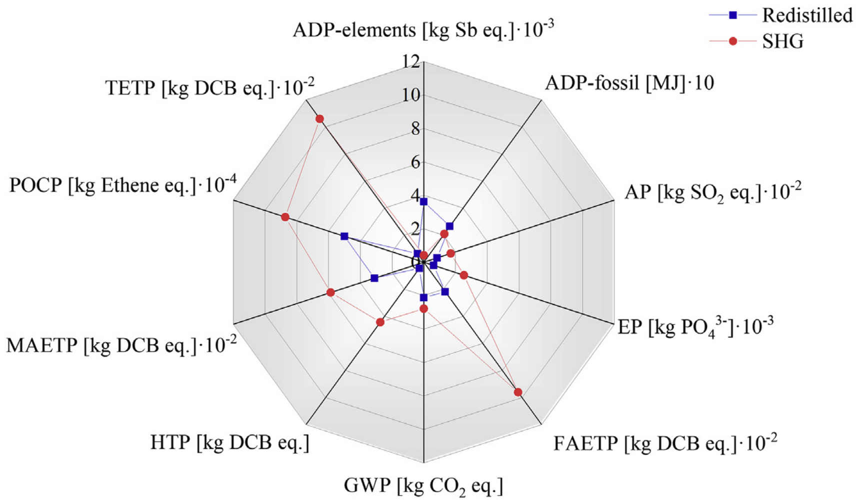

Fig. 5. Sensitivity analysis of the production of one kg of two types of zinc: SHG and "redistilled".

to air. However, the emissions of NOx to air are more notable in SHG zinc than in "redistilled" zinc. MAETP for SHG and redistilled zinc is motivated by the emission of hydrogen fluoride to air, but for SHG zinc, the additional copper emission to air increases its contribution.

3.3. *Comparative analysis of the zinc coating and painting*

Zinc production is one of the main environmental impacts of the HDG process in addition to steel production. This section compares the production of zinc and paint to be used as corrosion protection medium for steel. The steps summarised in Fig. 6 have been followed to compare the protective zinc and paint coatings under the same ambient exposure. The classification of the corrosivity of the atmosphere is determined by ISO 9223 (2012), which indicates that C2 and C3 correspond to low and intermediate levels of corrosivity. For comparison, the category C3, which represents atmospheric conditions with intermediate pollution (5–30 μg SO_2/m^3), is selected.

The average thickness of the zinc coating under C3 atmosphere, 85 μm, is reported in ISO 1461 (2009). The corrosion rate determined by ISO 14713-1 (2017), declares that under C3 atmosphere the thickness loss is between 0.7 and 2.1 μm/y, before the first maintenance operation is needed. Considering 85 μm thickness of the protective zinc layer and the corrosion rate, the durability of galvanised steel can be estimated between 40 and more than 100 years, which is very high. In the case of the paint coating, the thickness is reported by ISO 12944-5 (2018). Under C3 exposure category, the average thickness of the paint coating should be between 240 and 260 μm to provide steel with very high durability. This means that the first maintenance operation should be carried out after 25 years as ISO 12944-1 (2017) describes. With this information, and the density of zinc and paint, the consumption per m^2 of steel before the first maintenance operation can be calculated. Finally, this consumption should be divided by the durability of each protection coating to obtain the amount of zinc and paint per m^2 of steel for one year of protection. In the case of zinc coating, the durability considered is the average between 40 and 100 years (70 years). With this data, the comparison can be performed. Specifically, a comparison between the two types of zinc explained in section 3.2, which are SHG and "redistilled", with the production of two types of paints, solvent, and water-based paint white, is shown in Fig. 7. Both types of paints are used for the protection of metals, but their composition differs, and this explains the differences shown in Fig. 7. Solvent paint has 17% binding agent, 16% pigments and fillers, and 67% solvent. Water paint is formed by water varnish, with a composition of 21% binding agent, 35% pigments and fillers, 40% water, and 4% solvent. The fraction of organic solvent employed determines the significantly higher CF differences of solvent paint, 0.040 kg CO_2 eq./m^2 steel for one year of protection, in comparison with the water paint. Water paint and SHG zinc have similar CF, 0.025 and 0.024 kg CO_2 eq./m^2 steel for one year of protection. Redistilled zinc is the protective coating with the lowest CF, 0.018 kg CO_2 eq./m^2 steel for one year of protection. There are water-based coatings that can efficiently protect

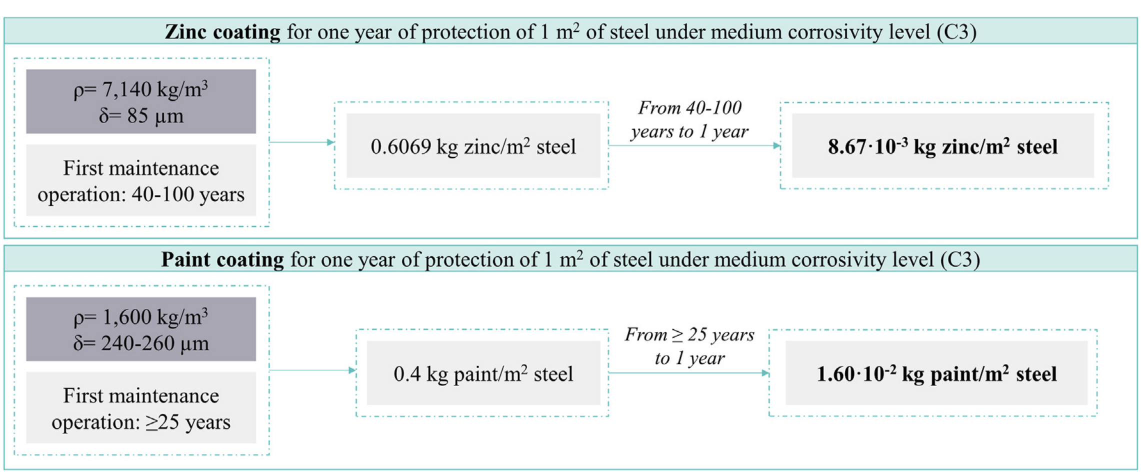

Fig. 6. Steps to perform the comparison between zinc and paint coatings for one year of protection to steel.

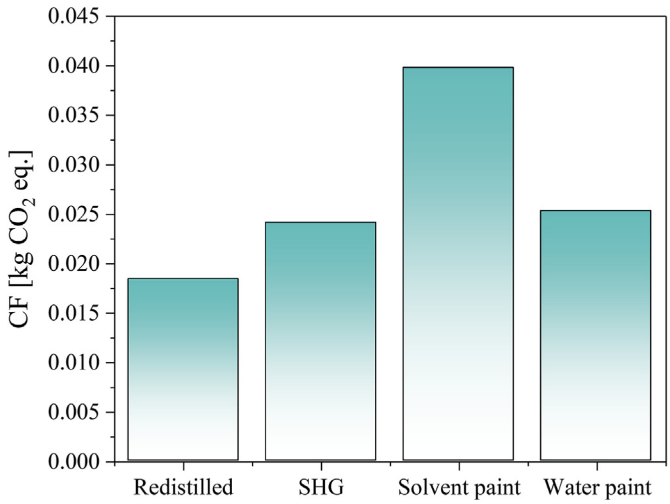

Fig. 7. Carbon footprint (kg CO_2 eq./m^2 steel) of the production of zinc (SHG and redistilled) and paint (solvent and water-based paint) for one year of corrosion protection of steel, and equivalent lifespan.

steel surfaces exposed to aggressive conditions (corrosivity > C5) (Fragata et al., 2006). Nevertheless, paint manufacturing technology, especially in the case of water-based paints, can influence the anti-corrosion performance of paint systems. As a result, similar systems supplied by different manufacturers work in different ways. This uncertainty does not occur in the case of using SHG zinc.

4. Conclusions

This paper presents the corporate carbon footprint of the hot-dip galvanising process, calculated for two HDG industrial installations (scenario 1 and scenario 2) located in Spain. Emissions from the production of steel and primary zinc (considered in Scope 3 of CF calculation) and the consumption of natural gas (Scope 1) were the hotspots of the HDG process with the highest contribution to the total CF. The influence of the purchased electricity (Scope 2) in both HDG plants was very low in comparison with the upstream processes (Scope 3). The energy credits obtained in the scenario 1 by the cogeneration unit improved its CF, albeit, this implementation is not possible in all HDG plants. These energy credits affect to Scope 1, and the material credits from the scrap valorisation have influence on Scope 3. Considering both credits, the total CF of scenario 1 was 1718.33 kg CO_2 eq./t galvanised steel, a 4.32% improvement respect to the calculation of CF without including the energy and material credits (1795.87 kg CO_2 eq./t galvanised steel). The carbon footprint of the HDG process could be mitigated using scrap as raw material in the steel production and increasing the efficiency of primary zinc consumption. Nevertheless, the energy consumption and resultant carbon impacts are limited by the galvanised steel demand that has an increasing trend.

As zinc plays a fundamental role in the reduction of the CF of the HDG process, the environmental impacts of two types of zinc were compared (SHG and redistilled zinc). The production of primary zinc is very intensive regarding the energy demand and use of resources. The environmental impacts associated with the zinc production depend on the quality of the zinc ore mine, such as the presence of silver and lead that affects to ADP-elements. Other alternatives aimed at resource efficiency, such as zinc recovery from spent pickling baths that are being investigated in the LIFE2ACID project could provide a groundbreaking technology to reduce the environmental impacts associated to primary resource usage and waste treatment. Additionally, the CF derived from the production of redistilled and SHG zinc and paint coatings required to protect 1 m^2 of steel/y was compared using solvent paint and water-based paint. The lowest CF corresponded to redistilled zinc (0.018 kg CO_2 eq./m^2 steel). The highest CF corresponds to solvent paint (0.040 kg CO_2 eq./m^2 steel), which is more reliable than water-based paint as anti-corrosion protection. This work confirms that the environmental assessment of individual HDG plants will help to set priorities in future improvements and will contribute to the sustainability of the galvanising sector by providing data for benchmarking.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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